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CURRENT CAPACITY OF CARBON NANOFIBER INTERCONNECTS

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ABSTRACT

Carbon nanofibers are promising interconnect materials for future military applications. How they behave in the elevated ambient temperature environment of a battle field is studied by performing series of current-induced nanofiber breakdown experiments.

1. INTRODUCTION

In a battlefield, the ambient temperature of electronic equipment is often raised significantly due to use of ammunition, explosion, and/or fire, but integrated circuits (IC) or chips embedded in the equipment should never malfunction. Interconnects are one of the most critical heat-generating elements on a chip, and their operation must be optimized in the context of the interplay between electrical and thermal transport, especially for military applications.

2. EXPERIMENTS AND MODELING

We study the current capacity and the associated current-induced breakdown phenomena of carbon nanofiber (CNF), which is actively studied as a next-generation on-chip interconnect material due to its excellent electrical and thermal transport properties and mechanical strength (Nihei et al., 2005). Current-induced breakdown occurs because of Joule heating, resulting in an open circuit in the network of interconnects. Current-induced breakdown in CNF interconnects simulates chip failure in the battlefield due to Joule heating and elevated ambient temperature, and heat dissipation via the underlying substrate would be the key to improving the reliability of the system.

Suspended and supported CNFs bridging gold (Au) electrodes are prepared and shown in Fig. 1(a) and 1(b), respectively (Kitsuki et al., 2008). For comparison, suspended and supported samples with tungsten (W)-deposited Au electrodes are prepared as in Fig. 1(c) and 1(d), respectively (Saito et al., 2008), and will be discussed later. As shown in Fig. 2(a), progressive current is applied to CNF devices shown in Fig. 1(a) or 1(b) (current stressing) and the total resistance between the two electrodes is measured. The results in Fig. 2(b) reveal that the total resistance decreases from the ~100 kΩ range to the kΩ range with current stressing, before breakdown occurs.

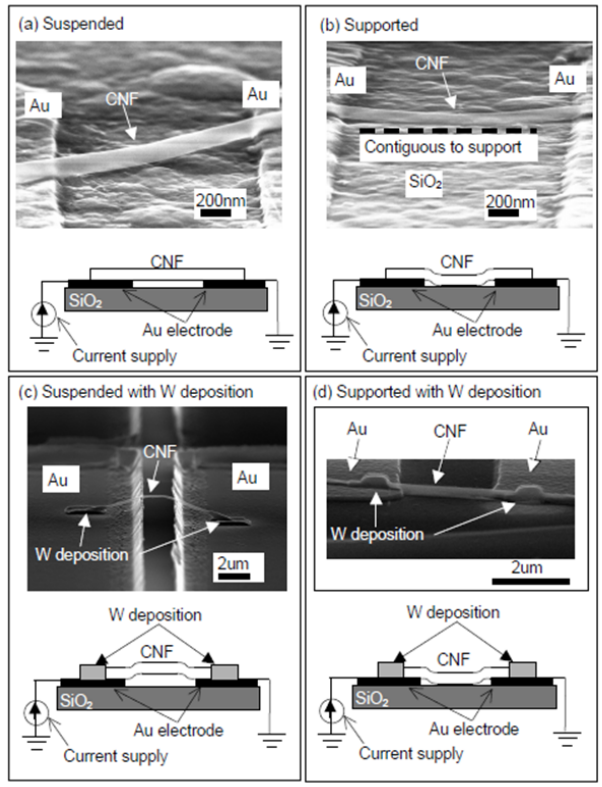

Fig. 1 Setup for current stressing experiments. (a) CNF suspended with Au electrodes. (b) CNF supported on SiO_2 substrate. (c) CNF suspended with W-deposited Au electrode. (d) CNF supported on SiO2 substrate with W-deposited Au electrodes. Upper figures show SEM image of a CNF sample at 75° tilted-angle view, lower figures illustrate schematics of electrical measurement.

Scanning Electron Microscopy (SEM) techniques are utilized to study the structural damage at and in the neighborhood of the breakdown location due to current stressing for suspended and supported cases. SEM images are shown in Fig. 3. It is found that breakdown occurs around the middle of a suspended portion of the CNF. In the suspended case (solid circles in Fig. 4), the measured maximum current density is inversely proportional to nanofiber length and independent of diameter. This result is successfully predicted with a one-dimensional heat transport model (Kitsuki et al., 2008). In the supported case (open circles in Fig. 4), the maximum current density is consistently higher because there is appreciable heat dissipation from CNF to substrate such that the CNF can stay cooler. The correlation between the maximum current density and electrical resistivity demonstrates the importance of local Joule heating, and confirming strong coupling between electrical and thermal transport in CNF interconnects.

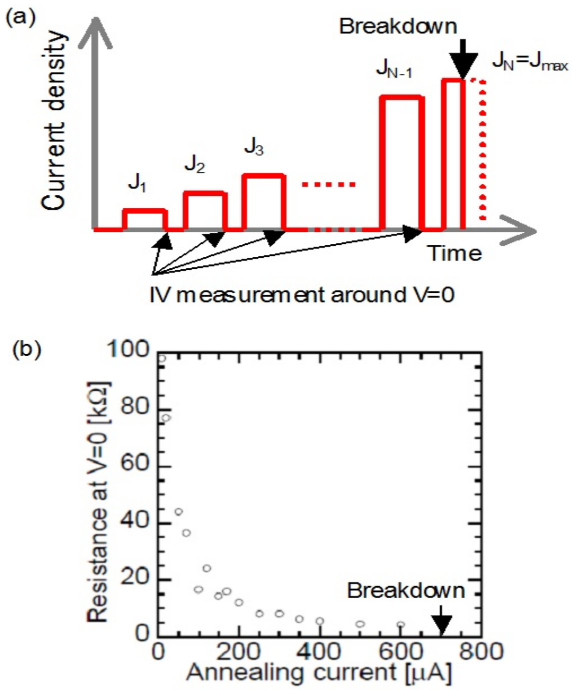

Fig.2 Resistance reduction of CNF device due to current stressing. (a) Schematic of successive current stressing cycles using stepwise increment of stressing current. (b) Resistance of the suspended CNF device at $V = 0$ obtained after each stressing cycle. In the W-deposited case, the total resistance stays practically unchanged.

For comparison, we examine W-deposited Au electrode contacts, where the CNF is sandwiched between the Au electrode and W-metal, suspended and supported in Fig. 1(c) and 1(d), respectively. Because of this sandwiched structure, the CNF is contacted to the electrode quite well, and the total resistance is low from the beginning, in the kΩ range, and current stressing has little effect on the total resistance. In the supported W-deposited cases (solid triangles in Fig. 4), the maximum current density is again consistently higher than in the suspended cases (open triangles in Fig. 4), and suspended data lie on the same straight line.

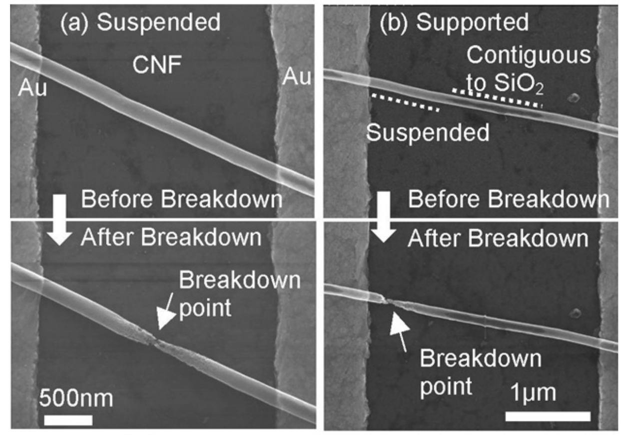

Fig. 3 SEM images of CNFs before and after current stressing at the top view. (a) CNF suspended with Au electrode. (b) CNF supported on SiO_2 substrate.

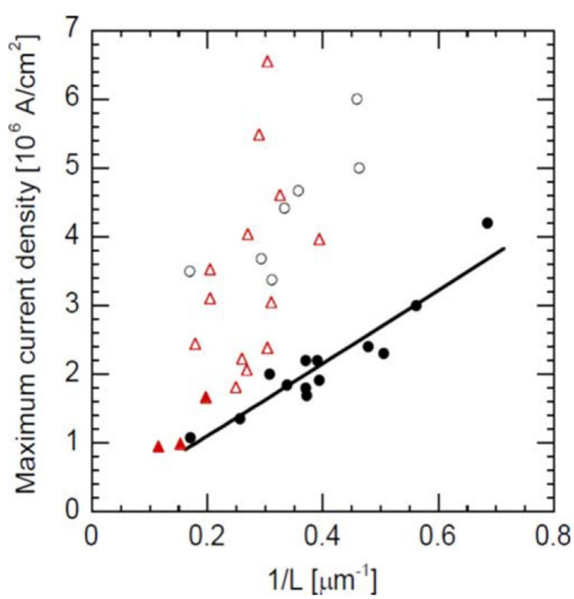

Fig. 4 Dependence of maximum current density J_{max} on CNF length L. The solid and open circles show the results for suspended and supported CNFs, respectively. Circles are contacts after current stressing, and triangles are W-deposited contacts, respectively. The straight line is a linear fit for suspended CNFs, as predicted by the heat transport model.

3. CONCLUISION

This study elucidates the physical mechanism for CNF breakdown and provides an important insight into heat dissipation in different device configurations, leading to subsequent design of CNF interconnects to improve performance and reliability. More detailed reports of this work are published in *Applied Physics Letters* (Kitsuki et al., 2008; Saito et al., 2008).

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